International Journal of Rock Mechanics & Mining Sciences 86 (2016) 269–281

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Deformation forecasting and stability analysis of large-scale underground powerhouse caverns from microseismic monitoring

Feng Dai [a], Biao Li [a], Nuwen Xu [a,*], Yilin Fan [b], Chuanqing Zhang [c]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower, Sichuan University, Chengdu, Sichuan, PR China
[b] China Three Gorges Corporation, Beijing, PR China
[c] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei, PR China

ARTICLE INFO

Article history:
Received 14 May 2015
Received in revised form
22 March 2016
Accepted 4 May 2016
Available online 17 May 2016

Keywords:
Underground powerhouse caverns
Microseismic monitoring
Excavation
Stability analysis
Deformation forecasting

ABSTRACT

To assess the stability of the underground powerhouse caverns and analyse the failure mechanism of the surrounding rock mass at the Baihetan hydropower station in southwest China, a high-resolution microseismic (MS) monitoring system was implemented in the left-bank underground powerhouse caverns. Based on the temporal and spatial distribution of MS events, the correlation between MS activities and construction was established, and three damage regions for the surrounding rock mass during excavation were identified. MS clusters were found to occur most often in stress-concentration regions of the underground powerhouse caverns and to result from various factors, including excavation-induced unloading and geological structure activation. The seismic source parameters (i.e., moment magnitudes and (S-wave) to (P-wave) energy ratios, E_s/E_p) of the three MS clusters demonstrate the different failure modes and risks of the surrounding rock mass. The temporospatial evolution of the MS activities, apparent stress, and cumulative apparent volume in localized rock mass during the period of a typical large deformation were used to develop a comprehensive analytical method for forecasting the deformation of the surrounding rock mass. Thus, this comprehensive analytical method, which incorporates MS monitoring, conventional monitoring, geological survey and construction, is promising for identifying the damage zones and forecasting the macro-deformation of the surrounding rock mass in underground powerhouse caverns subjected to excavation.

1. Introduction

Numerous large-scale hydropower powerhouses have been or are being constructed in Southwest China, such as in Xiluodu, Dagangshan, Baihetan, Wudongde and Houziyan. Due to the restriction of the topographic and geological conditions and the construction types of hydraulic structures, it is difficult to arrange the ground powerhouses. Rather, these large-scale hydropower powerhouses are arranged as underground types. Large-scale underground caverns usually pass through various geological structures and surrounding rocks. Thus, the stability of underground caverns subjected to excavation plays a significant role in engineering safety. Methods for effectively forecasting and controlling the rock mass instability induced by the excavation of underground caverns have been critical in geotechnical engineering practices.

Considerable efforts have been made to assess the stability of underground caverns subjected to excavation, including numerical analysis, model testing, and in situ surveys and measurements. For instance, Zhu et al.[1] numerically investigated the stability of underground caverns in three representative hydropower stations and obtained best-fit formulae to predict the displacements of the sidewalls of the underground openings. Cai et al.[2] employed a coupled continuum discrete model to investigate the acoustic emissions (AE) activities during the excavation of underground caverns. The AE activities at the AE sensor locations matched well with the field monitoring results. The simulation results also provided the distribution of stresses and displacement in the rock mass for excavation design of the underground caverns. Alejano et al.[3] introduced the finite difference method as a means of predicting the subsidence due to flat and inclined coal seam mining. Dhawan et al.,[4] Wang et al.[5] and Wu et al.[6] conducted stability analyses on underground caverns using finite element methods, discrete element methods and discontinuous deformation analysis. Jing et al.[7] applied both continuum and discrete modelling approaches for the safety analysis of radioactive waste

* Corresponding author.
E-mail address: xunuwen@scu.edu.cn (N. Xu).

http://dx.doi.org/10.1016/j.ijrmms.2016.05.001
1365-1609/

repositories, coupling thermal, hydrological and mechanical (THM) processes. Zeng et al.[8] introduced underground models to reveal the failure shapes and mechanisms of underground caverns under complex geological conditions. Zhang et al.[9] studied the mechanical behaviour of stratified rock mass during excavation using physical model tests on assemblages of aluminium blocks consisting of weak portions of the model material interspaced with model joints. They also applied a discrete modelling code to study the effects of discontinuities on the behaviour of stratified rock masses. Li et al.[10] analysed the measured data on the displacement, deformation convergence, bolt load and EDZ (Herein, the EDZ was defined as excavation damaged zone of tunnels or underground caverns, including the near-field EDZ and the far-field EDZ. The near-field EDZ was likely to be induced by either a direct result of the excavation process or caused by stress redistribution and concentration around the tunnel. The far-field EDZ was usually dominated by the elastic effects caused by redistribution of the stress field) of surrounding rocks and predicted the behaviours of the loosened zones to optimize the support systems for a large-span cavern in the Baishan hydropower station in China. Hibino and Motojima[11] investigated the deformation of more than ten large-scale underground hydropower stations by field measurements. Yan et al.[12] analysed the transient in situ stress redistribution on EDZ of a deep-buried tunnel using field tests and numerical simulation. Recently, in situ measurement techniques (i.e., global positioning systems, multiple position extensometers and convergence meters) have been widely used in underground engineering. These monitoring results can sufficiently reflect the stress and surface deformation characteristics of the surrounding rock mass and provide validation for the numerical and model testing results. However, these techniques are ill-suited to monitoring inner micro-fractures, which usually occur prior to the macroscopic deformation or catastrophic failure of the surrounding rock mass. Therefore, it is crucial to effectively capture the micro-fractures to evaluate the excavation-induced risks of underground caverns.

MS monitoring, as a three-dimensional, real-time monitoring technique, can detect the micro-fracturing signals of rock and record them as seismograms. By analysing the waveforms, the time, spatial locations and source parameters of MS events can be obtained. Over the past two decades, the MS monitoring technique has been developed into an effective approach to assess the engineering hazards in many fields within rock slope engineering[13–15] and underground engineering, such as deep mining,[16–22] oil and gas storage,[23] tunnels[24–28] and electricity generation from hot dry rocks.[29] For instance, Xu et al.[14,15] analysed the temporospatial distribution of MS events, explored the dynamic failure process considering MS damage and assessed the stability of the left-bank slope in the Jinping first-stage hydropower station in Southwest China. Lesniak and Isakow[18] performed a hazard analysis based on the MS clusters of a coal mine and correlated the evaluated hazard function to the time of occurrence of high-energy tremors. Tang et al.[20] analysed the apparent stress and seismic deformation of a copper mine and predicted areal hazardous seismicity. Cai et al.[24,25] proposed a tensile model to estimate fracture sizes from MS measurements and quantify the rock damage of the AECL Mine-by Experiment test tunnel. Tang et al.,[26] Feng et al.[27] and Chen et al.[28] explored and summarized a rockburst mechanism based on the correlation between MS evolutional laws and rockbursts induced by the excavation of deep-buried tunnels. However, within these studies, the MS monitoring technique has rarely been employed in the stability analysis and deformation forecasting of large-scale underground powerhouse caverns, particularly during real-time excavation.

In this study, an MS monitoring system was implemented in the left-bank underground powerhouse caverns under construction at the Baihetan hydropower station, Southwest China. By analysing the temporospatial distribution of MS events, a correlation between MS activities and excavation schedule was established, and the potential failure regions were identified. Furthermore, the formation mechanism of MS events and associated seismic parameters involving moment magnitudes and Es/Ep were investigated. Finally, a comprehensive method of forecasting the deformation of the surrounding rock mass based on MS activities, cumulative apparent volume and apparent stress was proposed.

2. Engineering background

2.1. Project description

The Baihetan hydropower station is currently under construction in the lower reaches of the Jinsha River between Sichuan and Yunnan Provinces, China. This project includes a 289-m-tall concrete double curvature arch dam, which controls a drainage area of more than 430,300 km^2. The two left- and right-bank underground main powerhouses contain eight units each, making this station the second largest in the world, with a total installed capacity of 16,000 MW. The left-bank large-scale underground powerhouse caverns are located in the upstream mountain of the dam, buried at a depth of 800–1050 m horizontally and 260–330 m vertically. These caverns mainly include pressure pipings, the main powerhouse, omnibus bar caves, the main transformer chamber, the draft tube bulkhead gate chamber, tailrace surge chambers and tailrace tunnels. The four main caverns (from upstream to downstream: main powerhouse, transformer chamber, draft tube bulkhead gate chamber and tailrace surge chamber) are arranged in parallel. The excavation dimensions of the main powerhouse are 438.0 m in length, 34.0 m in width, and 88.7 m in height. The designed excavation sizes of the main transformer chamber are 368.0 m in length, 21.0 m in width, and 39.50 m in height. The designed excavation dimensions of the draft tube bulkhead gate chamber are 374.5 m in length, 15.0 m in width, 94.0 m in height, while the four tailrace surge chambers have similar excavation dimensions of 44.5–48.0 m in diameter and 77.25–93.0 m in height. The thicknesses of the rock pillars between adjacent main caverns from upstream to downstream are 60.65 m, 40.95 m, and 46.95 m.[30] The layout of the left-bank large-scale underground powerhouse caverns is illustrated in Fig. 1. The underground powerhouse caverns were constructed using a conventional drill and blast method. The main powerhouse, transformer chamber and tailrace surge chambers were excavated using 10, 5 and 7 benches, respectively. The specific stratified excavation scheme of the underground group of caverns is shown in Fig. 2. Currently, four main underground caverns are being excavated at the first bench.

2.2. Formation lithologies

The left-bank slope of the hydropower station is steeply inclined toward the upstream side of the valley. Fig. 3 shows a typical formation cross-section of the left bank diversion power generation system along the 4# unit. The specific formation information is shown in Table 1. Overall, the diversion power generation system has a monoclinic formation, and the attitude of the basalt flow layer is with a strike of N42°–45°E, SE tendency, and a dip angle of 15°–20°. From upstream to downstream, the formations are in turn $P_2\beta_4$, $P_2\beta_3$, $P_2\beta_2$, and the lithologies include aphanitic basalt, oblique tholeiite, amygdaloidal basalt, breccia lava, tuff, and other materials. It is noteworthy that $P_2\beta_3{}^3$, $P_2\beta_3{}^2$ and $P_2\beta_4{}^1$ are mainly composed of the first, second, and third category of columnar jointed basalt, respectively. Furthermore, tuff